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Creation of a Learning Factory for Cyber Physical Production Systems

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Abstract

The development of Cyber Physical Production Systems (CPPS) is currently the dominant research topic in production and automation engineering. Therefore the underlying objective of this paper is to upgrade an existing centralized production laboratory to a CPPS learning factory. Key aspects of CPPS are interconnection on system level and with superordinate structures. This implementation, the comparison with state of the art production control systems and the utilization in university seminars are subjects of the paper. For example the enhancement enables the realization of manufacturing various products at the same time, mass customization aspects and automatic production of new products.

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Keywords: Coordination; Adaptive control; Reconfiguration

1. Introduction

Production systems face a profound technological conversion through the implementation of modern information and communication technologies. [1] Former reacting machines will be equipped with additional self-guiding technologies for self-contained execution and decision making. This conversion is part of an upcoming industrial evolution including subjects like Cyber Physical Production Systems (CPPS), industrial internet and factories of the future. This conversion was among other things triggered by the customization-movement of products. Fulfilling individual customer demands with affordable products require flexible and adaptable production processes. This flexibility and adaptability can be reached through a technological penetration of modern information and communication technology [2, 3]

Current automation solutions cannot face these challenges and therefore new approaches for production planning and control, manufacturing processes and automation technology are necessary. These new forms of production control and flexible manufacturing increase the complexity of production systems especially concerning information processing and software engineering.

To meet these challenges and prepare aspiring engineers for related issues, a learning factory for dealing with Cyber Physical Production Systems was created. An existing centralized PLC-controlled production laboratory was upgraded to a decentralized controlled Cyber Physical Production learning factory. This decentralization was implemented through the application of single-board computers with proprietary controlling heuristic. The single-board computer enhance existing control units regarding connectivity and condition monitoring. Each equipped machine knows its own status and has access to information of the production system. By adding controlling heuristic to every single-board computer a self-controlling production planning and control system is achieved. To teach the differences between the decentralized system for CPPS and the PLC-based centralized controlling system, the new system was developed as an extension, respectively alternative to the existing one. Working with both, centralized and decentralized controlling system, within learning factory seminars makes experiencing the differences according to performance, traceability and controllability possible.

This paper describes the underlying concept of the learning factory for Cyber Physical Production Systems. After a description of the former production laboratory and the state of

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the art of similar learning factories the CPPS learning factory is described. Finally the teaching concept of the learning factory is illustrated.

2. Laboratory for flexible industrial automation

The former laboratory for flexible industrial automation served as a research platform for current automation and production subjects and for academic courses. The laboratory consists of two manufacturing cells (a turning machine and a machining center) and an assembly station with a human-robot-collaboration robot. The machines are connected through a material flow system and additional industrial robots for workpiece handling and material supply.

The components are linked with each other by computer systems. The production procedure can be executed automatically. Figure 1 shows the laboratory in the current expansion state.

In the past several courses were carried out in the laboratory:

- *Exercise Robotics*

Students learn online and offline programming methods for different robots. The online programming is lectured via the teach-in procedure directly on a 6-axis robot. The first task is to implement a pick-and-place operation. For learning offline robot programming the existing robot cell shall be modeled and the same procedure of the online programming shall be programmed. After finishing this, the task of the students is to model a robot cell to execute different tasks (e.g. paint job, assembly, etc.). The last task is programming another pick and place operation on the collaborative two-arm robot.

- *Exercise PLC-technology*

In this exercise basics of pneumatic drives and programmable logic controllers (PLC) are taught in a practical manner on three different test rigs.

- *Exercise NC-programming*

NC manufacturing is taught via operating a turning machine, a milling machine, machining accessories and different CAM and CAD-programs. After learning the basics of machining with pre-defined demonstrators the students develop their own parts and deploy the resulting machining tasks on the machines.

- *Lecture Industrial Production*
- *Lecture computer-integrated manufacturing*
- *Project Laboratory "Digital Factory"*

In the project laboratory students work on a single project for four weeks as teams of at least five. The project consists of a planning or optimization task which is usually provided by an industrial company and can be simulated partially in the laboratory. Usually material flow simulation, workflow simulation and workstation simulation tools are used for processing the task. In addition to the modeling and simulation of the system, project management, teamwork, and presentation skills are trained.

At the moment a remote controlled car is used as a demonstrator. The demonstrator consists of the following produced parts:

- Additive manufactured chassis
- Milled car-platform
- Turned rims

All other parts like motors, wheels and motor control are bought separately. The concept of the demonstrator is based on a configurator model. Each part can be chosen and modified by the customer. For example motor power, chassis geometry, color, battery capacity can be changed according to customer needs.

After manufacturing the RC-car is assembled. All machines are connected through a single PLC: The PLCs main task is to control the material flow system via Profibus and to communicate with all subordinate machines (e.g. milling and turning machine). Through RFID-chips the position of all shuttle are determined. The production orders for the laboratory are entered in a pc and are transmitted to the PLC through an OPC-connection. The PLC tries to execute these orders based on their finish date and a user-defined priority by controlling machines, material flow shuttle and production sequence for assembly. In the beginning the raw material is placed on a workpiece carrier system on the shuttle. Afterwards this raw material is processed through the different machines.

3. State of the art

3.1. CPPS

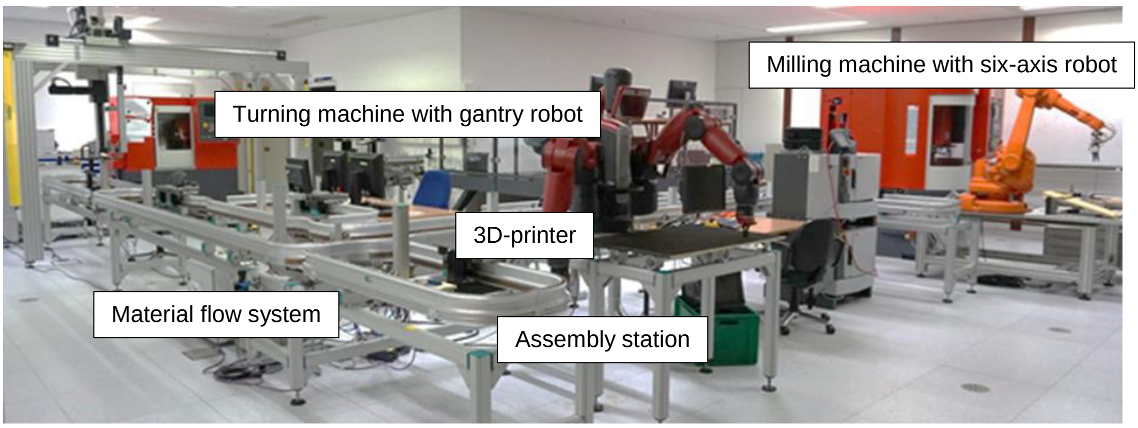

Figure 1. Laboratory for flexible industrial automation

CPPS were introduced to cope with the arising challenges of an individualized and flexible production. [4, 7] A CPPS consists of linked, collaborating Cyber-Physical Production Devices (CPPD). A CPPD is an embedded system which has an additional networking interface to communicate with other CPPDs [5]. Its task is to control or observe physical production processes through sensors and actors. With the aid of sensors cyber-physical systems are able to directly collect, process and evaluate data, while actuators allow them to react to changes and digital communication facilities allow them to interact with other cyber-physical systems. [6]

The implementation of CPPS will lead to significant changes especially in manufacturing processes and production control systems. The most significant features of CPPS are connection to computational services and among CPPS itself. Connections with services help CPPS accessing information available in software systems (like ERP, MES) and the Internet (for example for material and energy prices). Through the connection of multiple CPPDs, the data exchange among them and connections to superordinate collaboration platforms, CPPS can gain holistic information on their given tasks. Therefore CPPS are qualified to take decision and execute them self-contained. This concept assumes that no superordinate controlling system, which controls all elements of the production system is necessary in such an environment. This concept leads to an idea of dividing manufacturing processes into certain decentralized controlled autonomous production systems. [11]

Because CPPS can gain holistic information on their given tasks, they are able to execute decisions regarding production control by themselves without superordinate controlling systems. Every production system can determine its production sequence by itself [14]. The current dogma of a centralized production control illustrated by the automation pyramid is questioned by this decentralized computational intelligence. Hence central enterprise control elements, like Enterprise Resource Planning System (ERP), production planning system (PPS) and manufacturing execution system (MES), do not need to break down orders to the single production processes and units. This conversion is shown in Figure 2. [2]

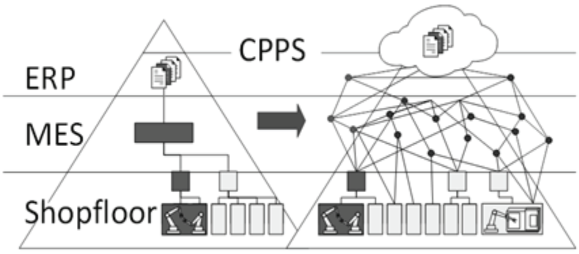

Figure 2: Decentral organization of the production [2]

3.2. CPPS learning factories

Due to the fact that CPPS are a dominant research aspect in production engineering many academic institutions implemented elements of this concept in existing learning factories. In the following learning factories with the focus on elements of CPPS are described.

The SmartFactoryKL realized a flexible production scenario based on modular manufacturing units, which can be flexibly changed and adapted. Main elements of Cyber Physical Systems like adaptability, plug & produce and decentralized control via RFID are implemented in this concept. Through standardized interfaces, different modules can be mounted and dismounted for creating the desired product line. Each module serves for a certain task like assembly, storage, production etc. [13]

The Demonstration Factory of the RWTH Aachen illustrates a complete production process for motorless go cars. In [10] a model is introduced which describes how different elements of CPPS can be shown and teached in the Demonstration Factory. The underlying learning factory concept is more about teaching students to deal with the consequences of CPPS than focusing on the implementation of CPPS-elements - especially regarding production control systems.

The IFA Learning Factory described a concept for the implementation of CPPS in their learning factory in combination with logistic models. [9] Other learning factories with focus on aspects of Cyber Physical Production Systems are for example:

- SmartFactoryOWL - Ostwestfalen-Lippe University of Applied Science and Fraunhofer IOSB-INA [12]
- Model factory Potsdam University [8]
- Model factory industry 4.0 of the chair for production logistics – University of Applied Science Rosenheim
- Teaching Factory - University of Patras [15]

4. CPPS implementation

Objective is to implement elements of CPPS (described in chapter 3) in the laboratory of flexible industrial automation for creating a CPPS-learning factory. Thereby a focus is placed on the following elements of CPPS:

- Flexible reconfiguration of production control systems
- Decentralization of decision-making and execution
- Modularization of the production system
- Adaptive connection of all production participants
- Plug and Produce
- Decentralized Production Planning System

On the basis of single-board computers (SBC) the concept of CPPS is implemented. Each selected unit of the production system is equipped with a single-board computer to add additional communication and information gathering and processing tools for creating Cyber Physical Devices. The concept includes the communication structure, a decentralized production control and the heuristic and algorithms of every device in the factory to enable an autonomous, decentralized production control system. Every device of the production system gets the ability to gather necessary information for its own operation and communicate its own status to other devices. A peer-to-peer framework enables the production system elements to communicate with other devices and consequently coordinate the production. Each device has the ability to send messages to other devices directly (via UDP) and broadcast messages to all devices (via TCP). In this communication structure every device assigns himself a role. In the current expansion state of the learning factory exist the following roles:

- Shuttles as part of the material flow system with the task to move material and work pieces among manufacturing stations
- Production units (so far assembly station, additive manufacturing station, milling and turning station)
- Monorail-Intersections in the material flow system which guide the way of the shuttle
- One central server (commander) who reads the orders from a superordinate cloud platform and provides them to the shuttles and therefore serves as an interface between decentral production and superordinate database.

These different roles respectively participants and the whole laboratory are shown in figure 3. The commander looks up new orders in the cloud platform and saves them into a database. Every agent in factory has access to this database and occupies orders according to deadline and a pre-defined priority of the order. The shuttle serve as the agents, which try to execute the order before the deadline. They are chief negotiators which communicate with all manufacturing units in order to execute their assigned orders. All manufacturing devices get requests from the shuttles and they try to proceed and execute these requests. For scheduling every device keeps a job sequence which is determined by deadline- and priority-based algorithms.

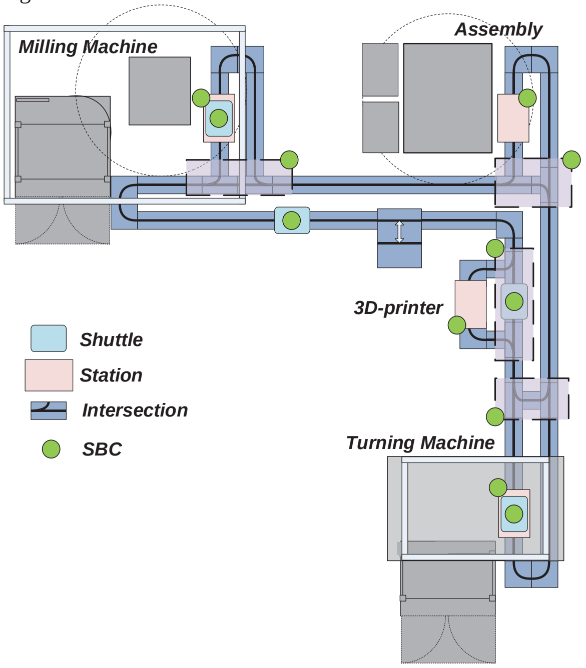

Figure 3: Learning factory layout with SBC-implementation

The shuttles get to know their position through reading barcodes placed on the material flow-system. Through this position information the shuttle capture the next position which subsequently can be used for routing (e.g. information about following intersections). The operation of additional handling devices like industrial robots is included in the associated manufacturing devices. All devices and their arrangement in the learning factory is shown in figure 3.

As demonstrator for production a remote-controlled car is used. It consists of an additive manufactured chassis, a milled car-platform, turned rims and additional purchased parts. The car is shown in the following figure 4.

The task of the production is to execute orders for this parts automatically. Each device gathers information of orders from a database in the internet. Each device was equipped with a single-board computer with two programs running: One application program and another communication program. The application program serves for executing its desired task. E.g. controlling the turning machine and industrial robot. The communication program is a peer-to-peer-network based program which is responsible for the communication between each device and therefore for the execution of superordinate tasks. The main task is to control and execute production orders by means of deadlines and priority.

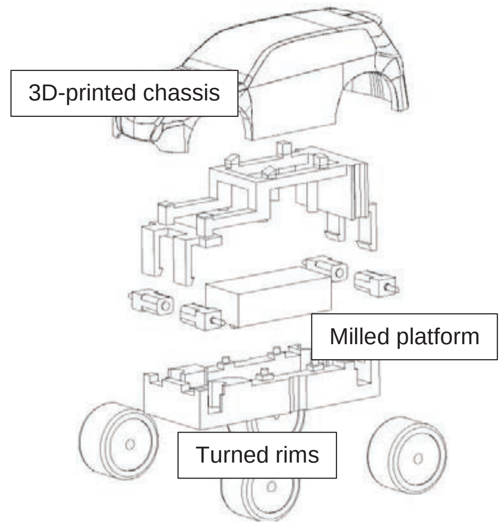

Figure 4: Demonstrator of the learning factory

This system is developed as an extension to the former PLC-based controlling-system. It is still possible to switch back to the old control process. The old control modules (mostly PLC-based) are still intact and can still be activated through switching cables. This coexistence serves as a basis for a comparison between this decentralized CPPS-production environment and the former PLC-based production control system.

5. CPPS – Learning factory

The focus of this learning factory is on the interconnection between product development and subsequent production of developed products. As mentioned in chapter 4 as demonstrator for development and production a RC-car is used. This RC-Car shall be optimized, respectively newly developed in development courses and afterwards produced automatically in the learning factory. Both, the execution of development and production are foundation of the teaching concept of the learning factory. Thereby basics of product development, like CAD, CAPP, engineering methods, production management and manufacturing technologies like robotics, numerical control, PLC-programming, manufacturing and assembly concepts and production management methods like lean production and six sigma are taught. Objective of the learning factory is experiencing product development and learning about the steps from a product idea to its production.

In at least two groups of at least three students the learning factory is carried out. At first a new model of the RC-Car shall be engineered. This includes the whole engineering process from derived requirements (like manufacturability, costs etc.) to new CAD models of selected parts. In this phase the students shall optimize the existing RC-car concerning several defined aspects (e.g. energy consumption, lightweight, lap time). The engineering includes the design of all manufactured parts, as well as programming and planning software and electrical control of the RC-car. A complete product model is derived. Afterwards the manufacturing of the car is prepared. Therefore the machining task is described by models and afterwards the NC-code is programmed. This includes generating NC-code for all parts and creating working and assembly plan. Additionally the machining tasks shall be described by semantic models. The semantic models are basis for the automatic deployment and execution of the parts. They describe the allocation of the developed parts to the machines. This procedure is described in the following figure 5.

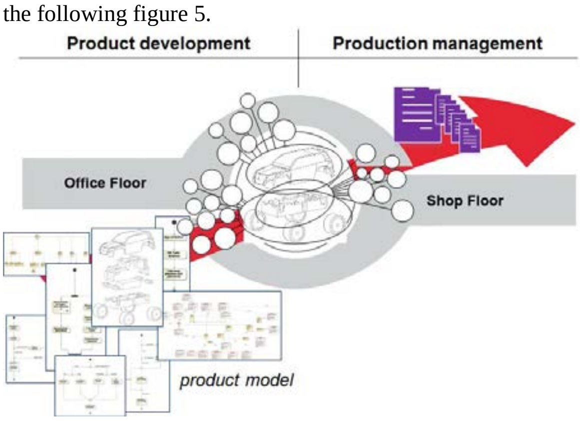

Figure 5: Learning Factory procedure

After creating this new model a set of cars shall be produced in different production scenarios to teach production control and management. In every production scenario a sequence of production orders needs to be executed. The scenarios shall illustrate the differences between the old PLC-controlled and the new decentralized controlling-system. In every scenario the students need to prepare the production system and plan the production sequence according to parameters (like customer retention, order volume and desired deadline) before starting it. In the PLC-controlled scenario a job sequence for every machine needs to be created. In the new concept priorities need to be defined, because the job sequence is determined automatically by the machines. The performance of one scenario takes one hour. During production execution the students need to fulfil different roles. One student assembles the RC-cars, another one sets up the machines and manages the production and the others measure production indicators like processing time. During the operation a few failures (e.g. malfunction of a shuttle) are simulated. After the performance all measured data is analysed and improvements of production system and production control are discussed. Afterwards the improvements are implemented and another production sequence with a similar procedure is executed. Again process indicators are measured, analysed and compared with the first run. As third scenario a production task which cannot be satisfied (because of too many production orders and simulated failures) shall be carried out. In this scenario the process indicators also need to be measured and analysed.

The scenarios are executed for both systems: PLC-based controlling system and new decentralized intelligence controlling system. The decentralized production control highly differs from existing approaches. Students shall learn the function of current planning methods. This includes the complete order processing. From creating new orders, ordering material and planning production capacity to planning the production in a manufacturing execution system. In total six scenarios are carried out. Afterwards the characteristics of both systems are discussed and both systems are compared. Not only the performance indicators are discussed, but also the effects of executing decisions that are based on computer algorithms and not by a human. In the first performances of the learning factory the following lessons were imparted:

- Basics of product development, work planning, production control, production management and software engineering for production systems are mediated in a practical manner. Thereby also skills of used software (e.g. CAD, CAPP, NC-programming) are gained.
- The interconnection between product development and subsequent production is comprehensible mediated (especially the creation of the working plan and the preparation of the manufacturing of different parts through 3d printing and NC-programming with subsequent assembly).
- Renewals through the implementation of the new concept. The decentralized computational intelligence through the single board computers compared to the centralized PLC-controlled system show different characteristics regarding to performance, interference of employees and behavior on errors.

The self-reliant planning characteristic of the new system offers many advantages especially concerning performance. The control systems takes over a lot of tasks which need to be carried out in the PLC-based controlling system by a human worker, but the possibilities of intervention are limited. Usually the self-controlling system is significantly better than the PLC-controlled system, especially because malfunctions are identified and a continuous rescheduling is performed. Besides the technical aspects also an awareness for the situation of the assigned employees is raised. After performing all scenarios improvements of the decentralized system are discussed. The improvements include the production system, the controlling system and the working situation for the participating workers in the learning factory.

6. Conclusion

This paper describes the concept of a CPPS learning factory, its implementation and its usage in academic courses and seminars. The key elements of CPPS, mainly the decentralized production control, the flexible composition of production units over the internet and the adaptive configuration of all participants (with plug and produce) were implemented. Additionally enables the retention of the old PLC-based control system the comparison between and investigation of the effects of CPPS. This paper has introduced a learning factory in which the characteristics of CPPS and their advantages, but also their disadvantages can be shown. The seminar concept illustrates how students can experience this change and be taught key competencies for working in modern, computerized productions.

The fist seminars showed the positive resonance of the participating students. Getting to know the challenges of the future productions and practically working self-reliant on automation and production projects with project responsibility is a great motivation.

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